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J.A. Kerns, J.R. Miller, and
L.T. Summers

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J.A. Kerns, J.R. Miller, and L.T. Summers
Lawrence Livermore National Laboratory
University of California
P.O. Box 5511, L-643
Livermore, CA 94550

Abstract

The poloidal-field (PF) coil set for the Tokamak Ignition/Burn Engineering Reactor (TIBER-II) consists of 24 solenoid modules, 16 of which are stacked inside the toroidal-field (TF) system at the center of the machine. These central solenoid modules operate at high-current densities, and maximum fields at the windings approach 14 T. Although TIBER II is designed for steady-state operation with noninductive current drive, other operating scenarios are also considered. In the pulsed or inductive mode, PF coil currents are ramped to induce plasma current. In this mode, peak fields approaching 14 T appear on the central solenoid modules at the ends of the stack; the required current densities in these modules approach 40 $A \cdot mm^{-2}$. The central solenoid modules are layer wound using cable-in-conduit conductor (CICC) with $(NbTi)_3Sn$ composite strands for improved high-field performance. Layer winding permits grading the conductor for maximum overall winding-pack current density and also results in less wasted space in the radial build of the machine. Cooling connections may be made at each layer of a module as needed. Current leads to the modules are routed through the high-field central bore. The central solenoid modules can easily support the centering load of the PF system, reducing the overall radial build of the machine and greatly increasing the limit on the number of pulse cycles imposed by fatigue considerations in the central solenoid.

Introduction

The TIBER-II has plasma current driven by non-inductive means as a baseline design. The machine also has pulsed capability where plasma current is driven by ramped PF fields. In both the steady-state and pulsed modes, the fields in some of the PF coils will reach nearly 14 T as the winding-pack current density approaches 40 $A \cdot mm^{-2}$. These fields occur in the central solenoid portion of the PF system, inside the TF system along the axis of the machine. The PF coils outside this central region do not present the same degree of difficulty for design and will not be discussed in this paper.

The high fields at the central solenoid windings limit the choices of superconductors, and we have chosen multifilamentary $(NbTi)_3Sn$ strands for the CICC. The CICC design process is described elsewhere [1]. In the first step of this process, a point conductor design is created to satisfy the primary operating conditions at the most critical point in the winding pack. Subsequent steps verify the point design against complex mechanical loads imposed on the conductor sheath and the capability of removing heat loads by flow of internal helium. In the following sections, we discuss operating conditions of the TIBER II central solenoid modules and how these conditions are accommodated by the conductor design process outlined in Ref. 1.

Mechanical Design

The performance requirements for the conductor in the central solenoid coils are given in Table 1. This list is already the result of several iterations, as described in Ref. 1. Characteristics of the conductor and winding pack designed to meet those requirements are listed in Table 2. This list reflects an optimization whereby CICC parameters are adjusted to ensure highest stability while meeting all the constraints imposed by the coil design. A special feature of the mechanical design of the central solenoid is noteworthy in this regard. As a space-saving measure, the central solenoid stack of TIBER II also serves as a bucking cylinder that bears the full centering load of the TF system. This role influences several features of the central solenoid modules design. First, the modules have moderately thick outer cases that bear the brunt of the TF centering load. Second, the modules are layer wound and current leads enter from the inner bore so that the winding packs fit

Table 1. Central solenoid parameters for the TIBER II PF system

Description	Symbol	Value
Magnetic field	B	14 T
Pack current density	J_{pack}	38 A/mm^2
Inlet bulk fluid temperature	T_{bulk}	4.5 K
Stored energy per module	E_s	60 MJ
Coil dump voltage	V_d	5 kV
Operating current	I_{op}	20 kA
Est. maximum hot spot temperature	T_{max}	130 K
Est. maximum quench pressure	P_{max}	37 MPa
Length of one turn		5.0 m

Table 2. Point conductor design for the TIBER-II central solenoid PF conductor.

Effective area of a turn, A_{eff}	523 mm^2	
Conductor + insulation size	22.9 mm square	
Conductor, cable-space cross section	289.9 mm^2	
Strand diameter	d_w	0.7 mm
Insulation thickness	t_{ins}	0.5 mm
Sheath material		JBK-75
Overall, winding-pack materials fractions:		
f'_{steel}	0.36	
$f'_{insulation}$	0.09	
$f'_{conductor}$	0.31	
f'_{He}	0.24	
Fraction of conductor in the cable cable space	0.56	
Fraction of copper in the conductor	0.35	

tightly against the outer cases for additional support. Finally, the outer diameter of the central solenoid stack is turned to a uniform diameter after assembly on a cross-shaped member that ties the modules together axially.

The response of the PF coils under the combined internal electromagnetic loads and external TF centering loads has been calculated using a modified version of STANSOL, a stress-analysis code for solenoids [2]. STANSOL treats only hoop and radial loads, but an accounting for the axial loads has been added using output generated by EFFI, a three-dimensional electromagnetic code [3].

The mechanical characteristics of the CICC winding pack are modeled for the STANSOL calculations as illustrated in Fig. 1. According to this model, we assume only the two walls of the sheath parallel to the load, and the insulation between, are effective in resisting the transverse loads; however, the entire sheath is active in resisting hoop loads. We have assumed the modulus of the cable to be negligible in these approximations.

Effective moduli for each direction are calculated consistently with the above assumptions and combined with the radial variation of the field and an external radial pressure from the TF system to produce the input for STANSOL. The results of the STANSOL calculation show that the winding pack of the coil remains in compression in both the radial and hoop directions (Fig. 2) throughout the windings. The hoop strain at a point in the winding pack is assumed identical to the sheath strain, and the STANSOL-generated hoop strains are modeled in the CICC optimization procedure.

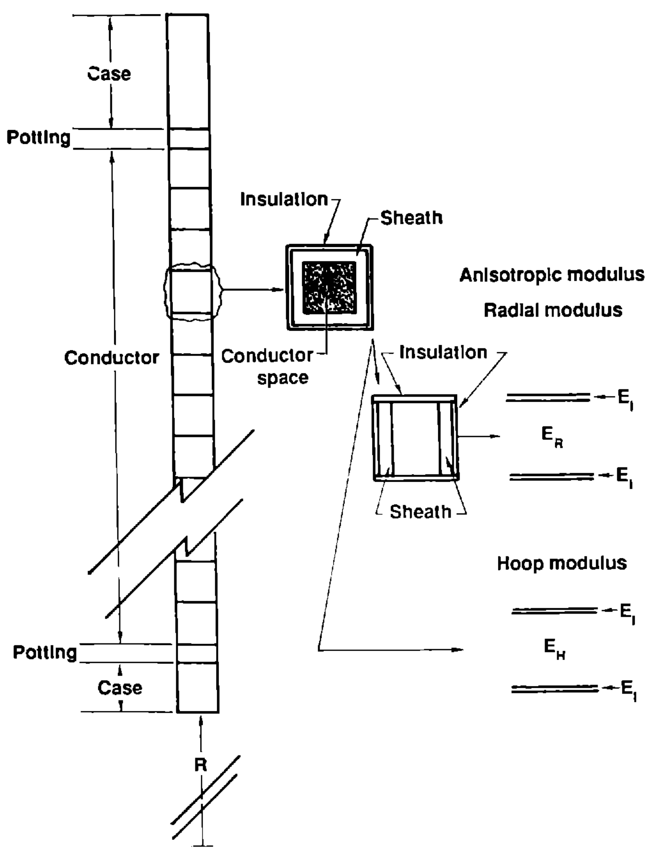

Fig. 1. STANSOL conductor model for the TIBER-II PF coils.

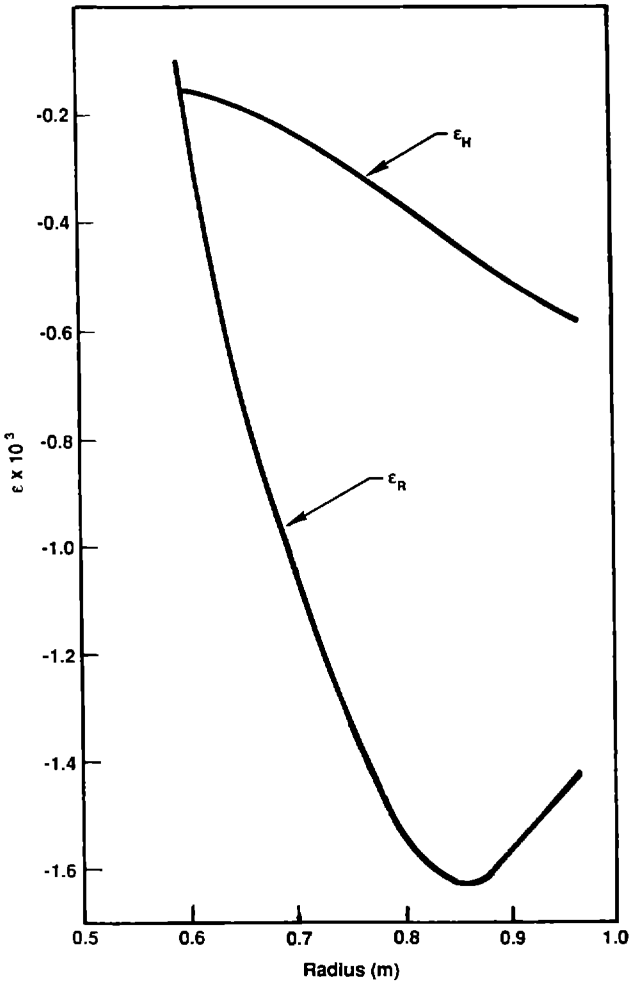

Fig. 2. Radial (ϵ_R) and hoop (ϵ_H) strains in the TIBER-II PF sheath as a function of radius into the PF coil.

The peak von Mises combination of axial, radial, and hoop stresses in the conductor sheath of a central solenoid module has been estimated to be 585 MPa. The allowable stress for the JBK-75 sheath material is 800 MPa [5]. The hoop strains associated with the full currents and fields in a free-standing central solenoid module (not loaded at the outer diameter by the TF system) are shown by the solid curve in Fig. 3 as calculated by STANSOL. These strains and the corresponding stresses are conservative for steady-state operation. However, when the PF coils are pulsed, the cyclic loading would lead to fatigue and reduced life for a free-standing PF design ($\leq 10^4$ cycles) [5]. The fatigue limit would be virtually eliminated by the design that bears the TF centering load since stresses in the windings are always compressive throughout each cycle. This is illustrated by the two lower curves in Fig. 3. The bottom curve shows the compressive hoop strain in the central solenoid module as a function of radius when the TF coils are fully charged (no PF current). When the PF and TF coils are both fully charged, the strain in the central solenoid modules is represented by the middle curve in Fig. 3.

Flow Analysis

The central solenoid modules are layer wound with helium flow connections to each layer. The helium flow paths will be approximately 60 m for inner layers and

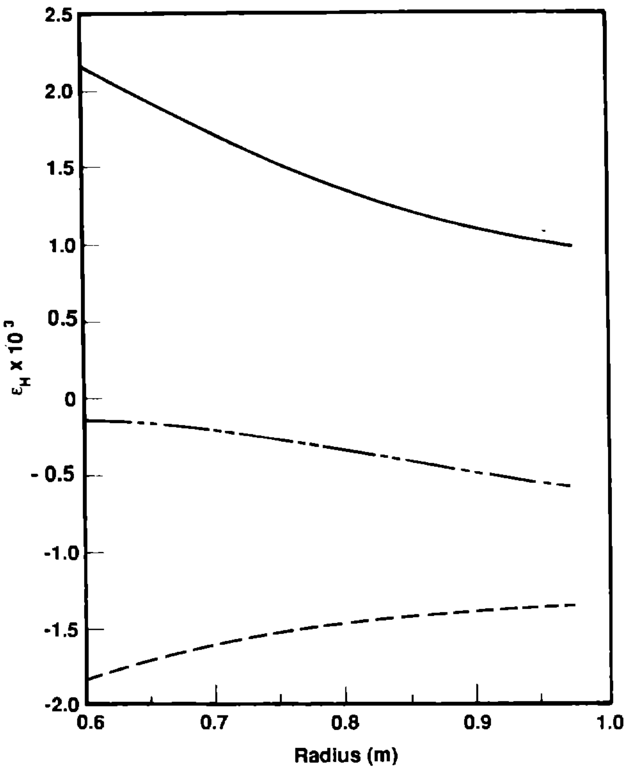

Fig. 3. Hoop strain across the TIBER-II PF coils for a free-standing coil (————), PF coil bucking TF coil radial loads with no current in the PF coils (- - - - - -), and when the PF coil is charged (— - - - —).

110 m for the outer layers. Because there is negligible heating for steady-state operation, the only losses result from frictional effects. The frictional losses are kept small by maintaining flow at Reynolds numbers of 10^4 or below. The flow analyses show that for helium inlet of 0.5 MPa and 4.5 K, a stability margin greater than 300 $mJ \cdot cm^{-3}$ is maintained everywhere along the PF conductor flow path.

Heating during pulsed operation poses a more severe cooling problem. Initial estimates indicate that the average heat generation in the central solenoid modules can be as high as 67 kW total to all coils [4]. The flow path through these modules is approximately one-third that of the TF coils, but the heat generated per cubic meter of coil is significantly larger. Superimposed on the steady heat load is a sharp deposition when the coils are ramped very rapidly for a brief period for plasma initiation. An initial analysis of the He flow through a module shows that it is possible to design the flow system to have an adequate stability margin (>300 $mJ \cdot cm^{-3}$) before the plasma initiation, but that the energy added to the He during plasma initiation can produce a zero or negative margin condition.

Conclusion

The conductor design in Table 2 fulfills the needs of the baseline, steady-state, TIBER-II design. This design is a starting point for the pulsed-mode of operation, but the estimated ac heat loads are high and the conductor or coil design needs further analysis. The mechanical design wherein the PF central solenoid also serves to support TF centering loads appears to have merit both for reduced machine size and for improved fatigue life.

Acknowledgments

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